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Abstract

Numerous unexpected operational issues relating to the abrasive nature of lunar dust, such as scratched visors and spacesuit pressure seal leaks, were encountered during the Apollo missions. To avoid reoccurrence of these unexpected detrimental equipment problems on future missions to the Moon, a series of two- and three-body abrasion tests were developed and conducted in order to begin rigorously characterizing the effect of lunar dust abrasiveness on candidate surface system materials. Two-body scratch tests were initially performed to examine fundamental interactions of a single particle on a flat surface. These simple and robust tests were used to establish standardized measurement techniques for quantifying controlled volumetric wear. Subsequent efforts described in the paper involved three-body abrasion testing designed to be more representative of actual lunar interactions. For these tests, a new tribotester was developed to expose samples to a variety of industrial abrasives and lunar simulants. The work discussed in this paper describes the three-body hardware setup consisting of a rotating rubber wheel that applies a load on a specimen as a loose abrasive is fed into the system. The test methodology is based on ASTM International (ASTM) B611, except it does not mix water with the abrasive. All tests were run under identical conditions. Abraded material specimens included poly(methyl methacrylate) (PMMA), hardened 1045 steel, 6061-T6 aluminum (Al) and 1018 steel. Abrasives included lunar mare simulant JSC-1A-F (nominal size distribution), sieved JSC-1A-F ($<25\text{ }\mu\text{m}$ particle diameter), lunar highland simulant NU-LHT-2M, alumina (average diameter of $50\text{ }\mu\text{m}$ used per ASTM G76), and silica (50/70 mesh used per ASTM G65). The measured mass loss from each specimen was converted using standard densities to determine total wear volume in cm^3 . Abrasion was dominated by the alumina and the simulants were only similar to the silica (i.e., sand) on the softer materials of aluminum and PMMA. The nominal JSC-1A-F consistently showed more abrasion wear than the sieved version of the simulant. The lunar dust displayed abrasivity to all of the test materials, which are likely to be used in lunar landing equipment. Based on this test experience and pilot results obtained, recommendations are made for systematic abrasion testing of candidate materials intended for use in lunar exploration systems and in other environments with similar dust challenges.

I. Introduction

Numerous unexpected operational issues relating to the abrasive nature of lunar dust were encountered during the Apollo missions. Issues recorded by astronauts on lunar extravehicular activity (EVA) were catalogued by Gaier (Ref. 1) and included abrasion on Apollo spacesuits leading to scratches and wear affecting visibility and pressure retention. The resultant fine-grained and highly angular shapes of lunar dust particles have been attributed to the continuous micrometeorite bombardment of the Moon and a lack of mechanical weathering, consequently making them especially abrasive (Refs. 2 and 3). Fine dust particles in this context are typically characterized by their size range of <1 to $50\text{ }\mu\text{m}$ (Refs. 4 and 5). Although specific definitions between groups vary, on average, researchers refer to particles with diameters less than $20\text{ }\mu\text{m}$ as “dust” (Refs. 6 and 7).

The National Aeronautics and Space Administration (NASA) Dust Management Project (DMP) has identified key physical properties of interest to the lunar science community. Abrasion’s importance for study was ranked as ‘high’ for future exploration missions because it affects any space system component that comes into contact with dust, especially having moving parts and/or has a seal. The DMP was created in the Exploration Technology Development Program (ETDP) at NASA following the results and assessment of the Exploration Systems Architecture Study (ESAS). One goal of the research being conducted within the DMP is to develop recommendations and standard testing protocols for evaluating the impact of lunar dust abrasion on proposed surface system materials and operations. Both two-body and three-body abrasion modes are currently being investigated for future NASA testing of lunar equipment in relevant environments using abrasives that parallel actual regolith, known as lunar dust simulants.

To avoid reoccurrence of detrimental equipment abrasion problems noted during Apollo, future lunar surface systems (LSS) used in missions to the Moon can be designed to take into account expected operational wear. To rigorously characterize the effect of lunar dust abrasiveness on candidate materials, a series of two- and three-body abrasion tests have been developed and conducted. Two-body scratch tests were initially performed to examine fundamental interactions of a single particle on a flat surface (Refs. 6 and 7). These simple and robust tests were used to establish standardized measurement techniques for quantifying controlled volumetric wear (Refs. 8 and 9). Subsequent testing involved a three-body abrasion technique designed to be more representative of actual operational interactions. For these tests, a new tribotester was developed to expose samples to a variety of typical abrasives and the lunar simulants JSC-1A-F, representative of the lunar mare region, and NU-LHT-2M, representative of the lunar highland region (both are based on the average chemical composition of Apollo samples). This paper discusses the apparatus, methodology and results obtained from initial testing.

II. New Test Methodology

The initial two-body abrasion baseline laid the foundation for conducting the more representative three-body tests. Instead of a single pass scratch, three-body abrasion better simulates the lifetime of a material by quantifying material removal in a set amount of time based on intended operational interactions. This test method is a derivative of the ASTM International (ASTM) B611 Standard that allows use of custom abrasives, i.e., lunar stimulants (Ref. 10). The test specimen is cleaned and weighed three times to determine the initial mass. From 20 to 80 grams of abrasive is fed onto the rubber wheel (as indicated in Figure 1) during the entire test time. The specimen is at the bottom of a vessel that holds loose abrasive and the rubber wheel forces the abrasive against the horizontal counterface (see Figure 1 for configuration). Mass change is used as the test metric. The tester is shut down after 450 revolutions (170 m). The test specimens are washed in water and Windex (S. C. Johnson & Son, Inc.) after testing and dried before reweighing (see Figure 2). The specimens are again weighed three times for a final mass average. Fresh abrasive was used for each test.



Figure 1.—Three-body abrasion tester (rotation direction indicated with curved arrow) with abrasive entry point on right side (indicated with straight arrow). The specimen sits at the bottom of the rotation wheel.

The test employed uses the same concept as ASTM B611 except that the testing equipment (Bud Labs, Rochester, NY) uses a rubber wheel and no water, just a dry abrasive, which is more applicable for Moon, Mars or other celestial body abrasion environments. The test is not a standard yet, as methods of feeding dust into the system are still being evaluated. The abrasion tester includes a 60 Shore A Neoprene wheel (12.7 mm wheel width, 109 mm diameter), with velocity of 0.17 m/s (30 rpm) and a force on the specimen of 55 N (12.3 lb).

Abrasives and material specimens used are summarized in Table 1 with number of tests conducted. Abrasives included: JSC-1A-F (nominal size distribution); sieved JSC-1A-F (less than 25 μm particle diameter prepared by NASA Glenn Research Center using a mechanical sieve); alumina (50 μm average particle diameter); and sand with AGSCO AFS 50/70 mesh (200 μm average diameter). A chemical or sieve analysis is not conducted on the later two abrasives because both are ASTM test standard abrasives and shipped as such. The sand is used in ASTM G65 and the alumina is used in ASTM G76 (Refs. 11 and 12). Material specimens that were abraded included: 6061-T6 aluminum (Al); 1018 steel (hardness of 60 HRB); 1045 steel (hardness of 50 HRC); and poly(methyl methacrylate) (PMMA).

TABLE 1.—THREE-BODY ABRASION TEST SUMMARY WITH NEW TRIBOTESTER
Number of Abrasive Tests

Material	JSC-1A-F	JSC-1A-F <25um	Alumina	Silica (Sand)	NU-LHT-2M
6061-T6 Al	3	3	4	4	3
1018 Steel	3	3	4	4	3
1045 Steel	3	3	4	4	3
PMMA	3	3	4	4	3

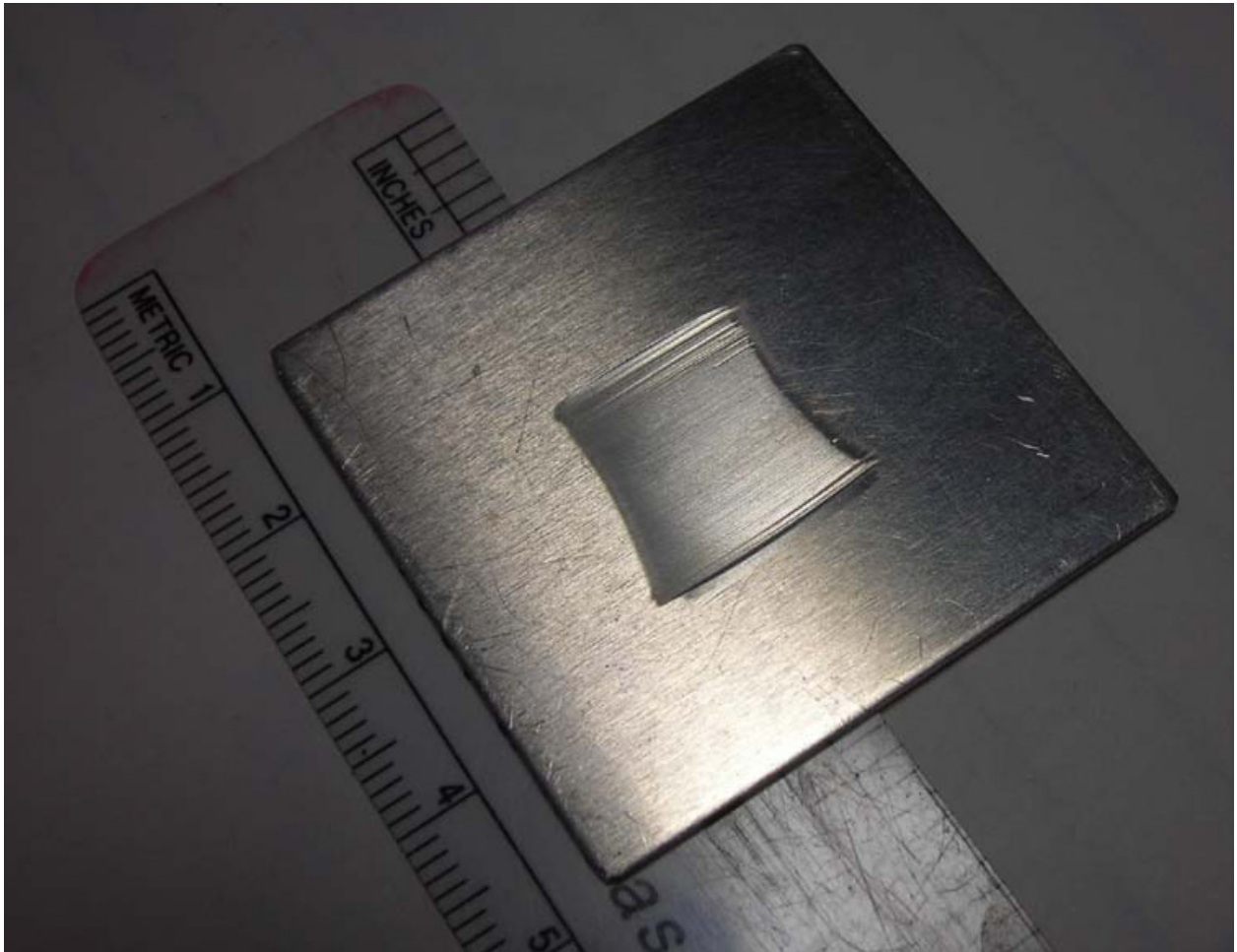


Figure 2.—Image of aluminum specimen after being abraded by alumina.

III. Results

The results (summarized in Appendix A) are graphically presented in Figure 3 and Figure 4 as wear volume loss in cm^3 after conversion using material densities (Ref. 13). Figure 3 represents the PMMA wear volumes from various simulants and Figure 4 represents the metal specimens wear volumes. The discussion following the results includes qualitative observations inferred from the data. Further tests would have to be repeated in multiple labs to establish quantitative statistical significance. The test materials selected represent the range of materials likely to be used in lunar landing equipment or other spacecraft missions that will voyage to planetary or asteroid surfaces.

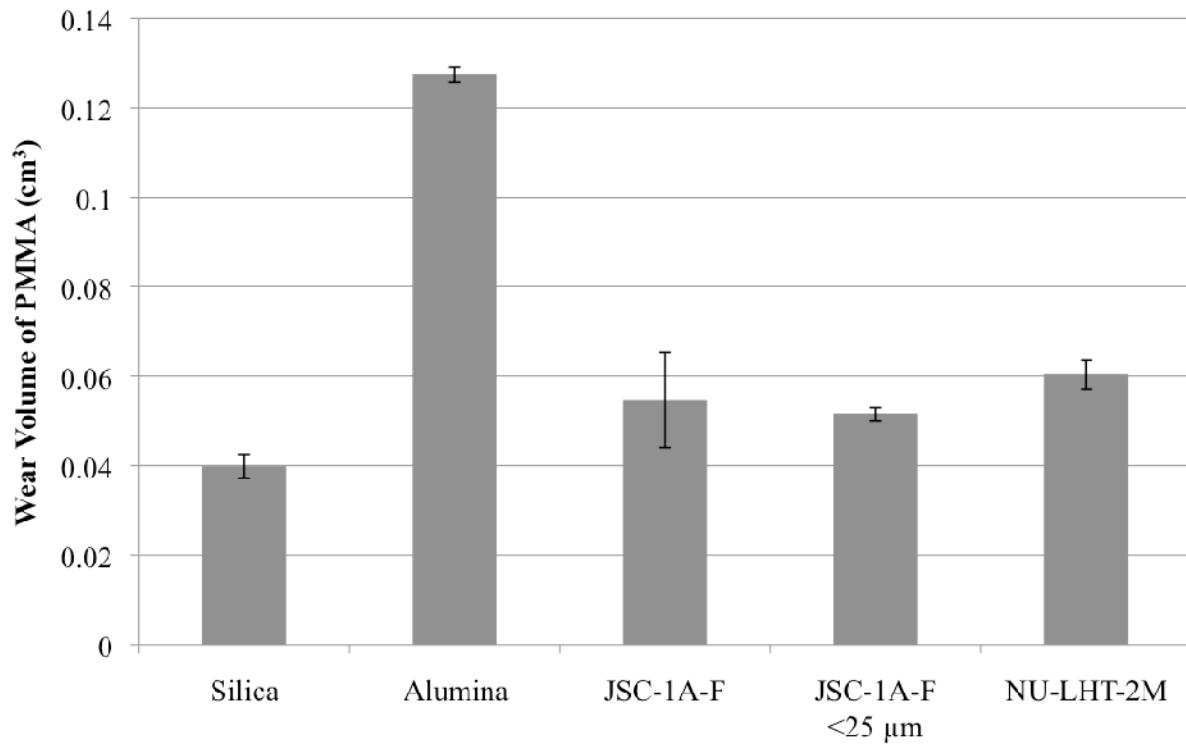


Figure 3.—Wear volume of PMMA abraded with new tribotester by various lunar simulants and abrasives.

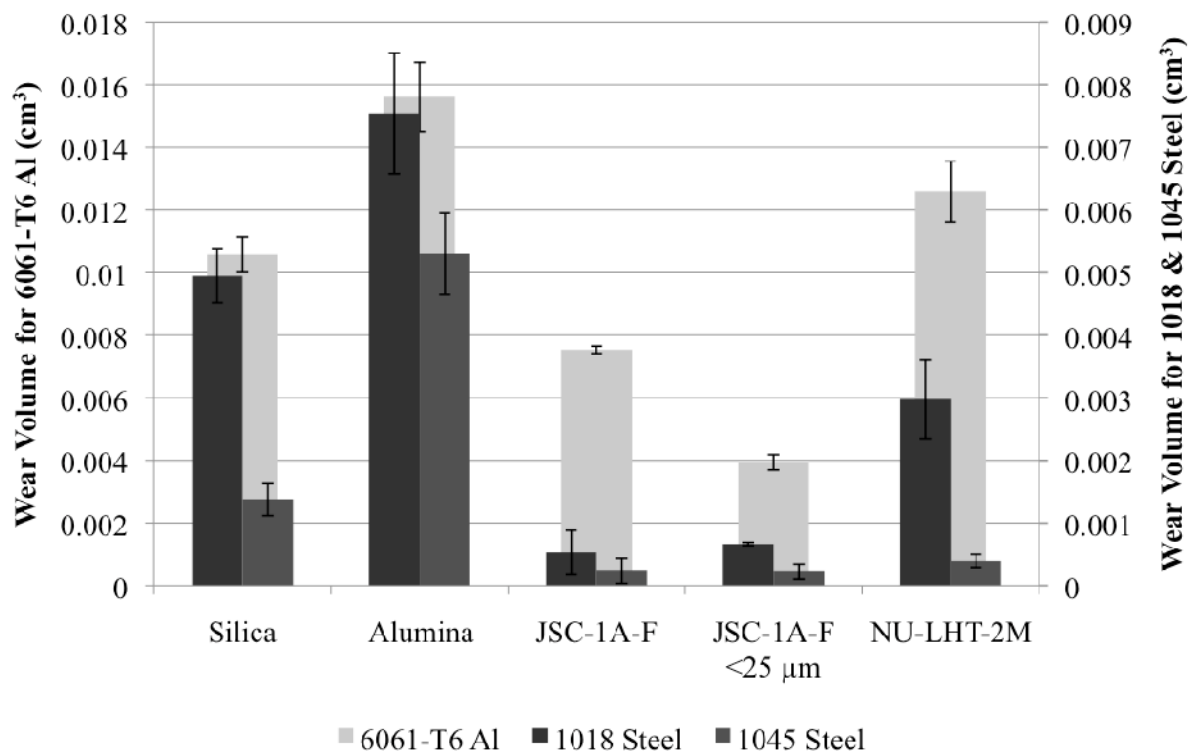


Figure 4.—Wear volume of metals abraded with new tribotester by various lunar simulants and abrasives.

IV. Discussion

Based on the experience and pilot results obtained from this testing, lunar dust simulants can be expected to produce a range of wear effects on various materials. The data indicate that lunar dust simulants have comparable abrasivity to silica on the softer test materials only (Al and PMMA). The tests results showed similar trends for wear volume in the different materials. Alumina powder dominated abrasion on all materials, resulting in the most volume removed. In general, steels showed good resistance to abrasion against the lunar simulants, aluminum is prone to abrasion by the simulants, and PMMA is very prone to abrasion by simulants.

The JSC-1A-F nominal particle size distribution produced more wear than the sieved version of the abrasive. This size difference may or may not be the reason for the difference in values obtained since the mineralogy is not uniformly distributed within the simulant by size fraction. This means that the larger particles removed by sieving might be harder minerals. Most of the abrasives were in the 25 to 100 μm range except the silica, which was closer to 200 μm . It was observed in the NU-LHT-2M simulant that there were large 500 μm pieces that would stall at the wheel's base upon contact, and when they did, a distinctive "crunch" was heard. Smaller particles are likely to polish materials, while the larger particulates may be causing the most wear. Therefore, selection of appropriate abrasive particle size and distribution will be critical for fully characterizing wear interactions using this device.

The simulants available are representative of the two main lunar regions (mare and highlands) so do not represent the full diversity of the lunar terrain. Further, recently available information by Cole et al. (Ref. 14) on the strength of lunar regolith grains as compared to terrestrial materials of similar composition has demonstrated that lunar plagioclase grains can have two to three times less mechanical strength than terrestrial material when compressed. Cole et al. paper clarifies why the terrestrial counterparts are considerably more robust - the lunar grains appear to be composed of much smaller fragments fused or sintered together. This structure is considerably weaker at the fragment boundaries than the internal crystal energies holding mineral crystals grains together thus leading to enhanced friability. If actual lunar grains were applied to the testing procedure described in Section II of this paper, one would expect to see considerably less damage due to the polishing action of the fine fragments as they are released by mechanical crushing. This means that laboratory tests should be conducted with abrasives that are specific to the intended location of future missions. A similar approach can be used to develop testing protocols for exploration of Mars, asteroids or other planetary surfaces.

An alternative to location specific abrasive selection would be to over design a system to take into account a worst-case wear scenario. For example, pure alumina could be used as a single test abrasive in place of specific lunar simulants if it is consistently shown to produce the most significant abrasive wear in future tests. This approach would come at a mass penalty, but might help with risk assessment or in establishing engineering design safety factors. Ultimately, using systematic abrasion testing and measurements can aid in material selection for lunar surface systems, as well as for other spaceflight or terrestrial environments with similar dust challenges.

V. Conclusions and Recommendations

The new tribotester demonstrated that well-controlled data could be obtained using a variety of dry abrasives and test materials. This device provides a versatile means of conducting material abrasion testing recommended for planetary exploration because of the flexibility to systematically change abrasive variables such as grain size. Future upgrades to the simulations could add control of humidity, temperature, and pressure, as needed. This test method is simple and inexpensive, making it attractive to the space engineering design community to either adopt directly or contract out to a lab for analysis. Future work is planned to address the effects of varying the alumina average grain size. Other suggested tests include varying the applied load on the abrasion wheel, the rotation speed of the wheel, and test duration in the case of abrasion resistant materials.

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Appendix A.—Summary of Data From Three-Body Abrasion Testing

Material	Abrasive	Wear volume, cm ³	
		Mean	Std. Dev. (n) ^a
6061 Al	JSC-1A-F	0.0075	0.0001 (3)
1018 Steel	JSC-1A-F	0.0005	0.0004 (3)
1045 Steel	JSC-1A-F	0.0002	0.0002 (3)
PMMA	JSC-1A-F	0.0546	0.0106 (3)
6061 Al	Silica	0.0106	0.0006 (4)
1018 Steel	Silica	0.0049	0.0004 (4)
1045 Steel	Silica	0.0014	0.0003 (4)
PMMA	Silica	0.0399	0.0027 (4)
6061 Al	Alumina	0.0156	0.0011 (4)
1018 Steel	Alumina	0.0075	0.0010 (4)
1045 Steel	Alumina	0.0053	0.0007 (4)
PMMA	Alumina	0.1274	0.0017 (4)
6061 Al	JSC-1A-F <25 μm	0.0039	0.0002 (3)
1018 Steel	JSC-1A-F <25 μm	0.0007	0.0000 (3)
1045 Steel	JSC-1A-F <25 μm	0.0002	0.0001 (3)
PMMA	JSC-1A-F <25 μm	0.0515	0.0015 (3)
6061 Al	NU-LHT-2M	0.0126	0.0010 (3)
1018 Steel	NU-LHT-2M	0.0030	0.0006 (3)
1045 Steel	NU-LHT-2M	0.0004	0.0001 (3)
PMMA	NU-LHT-2M	0.0604	0.0032 (3)

^an = number of tests

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